FLUID MECHANICS

Chapter 2: Fluid Properties

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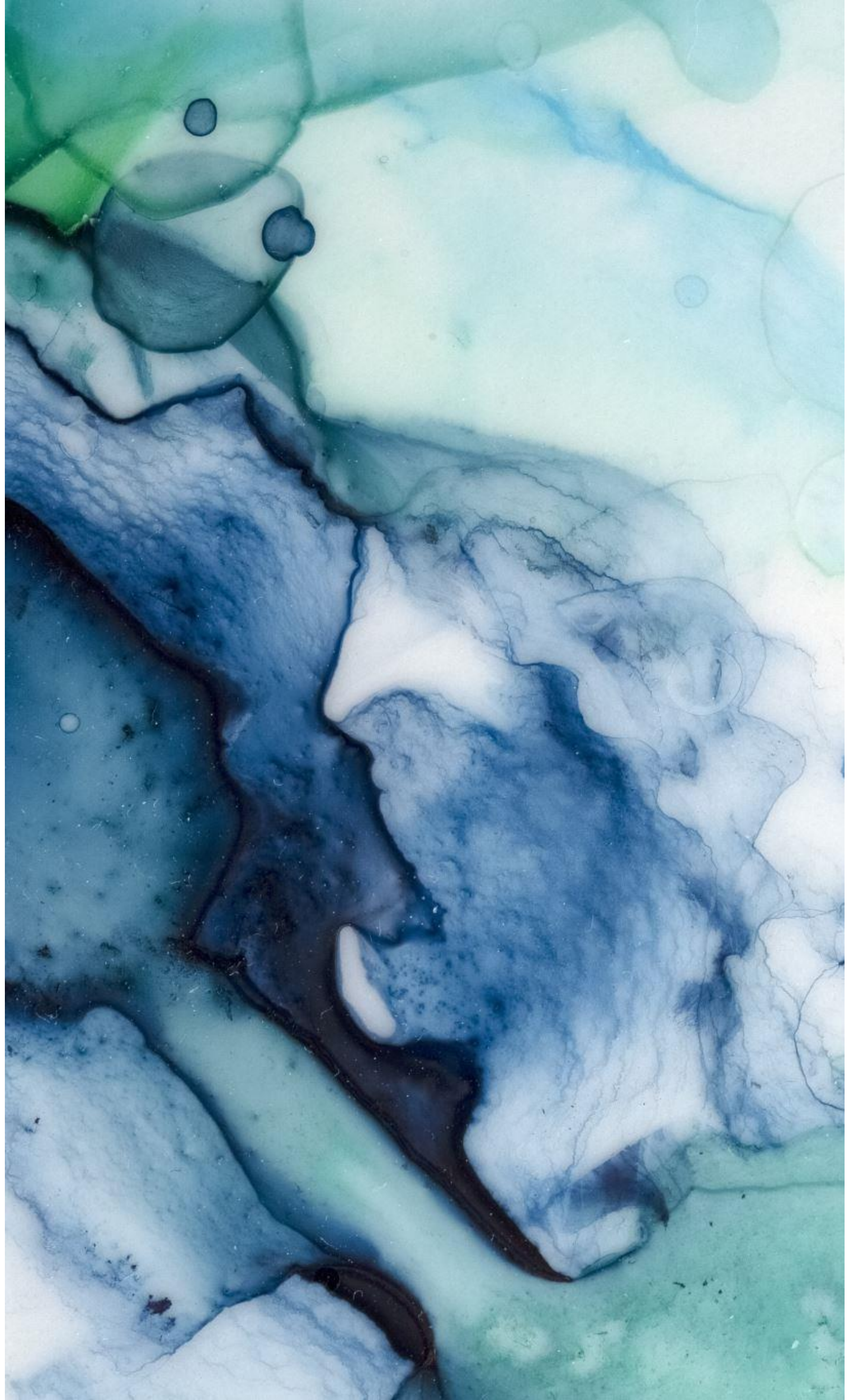


Objectives

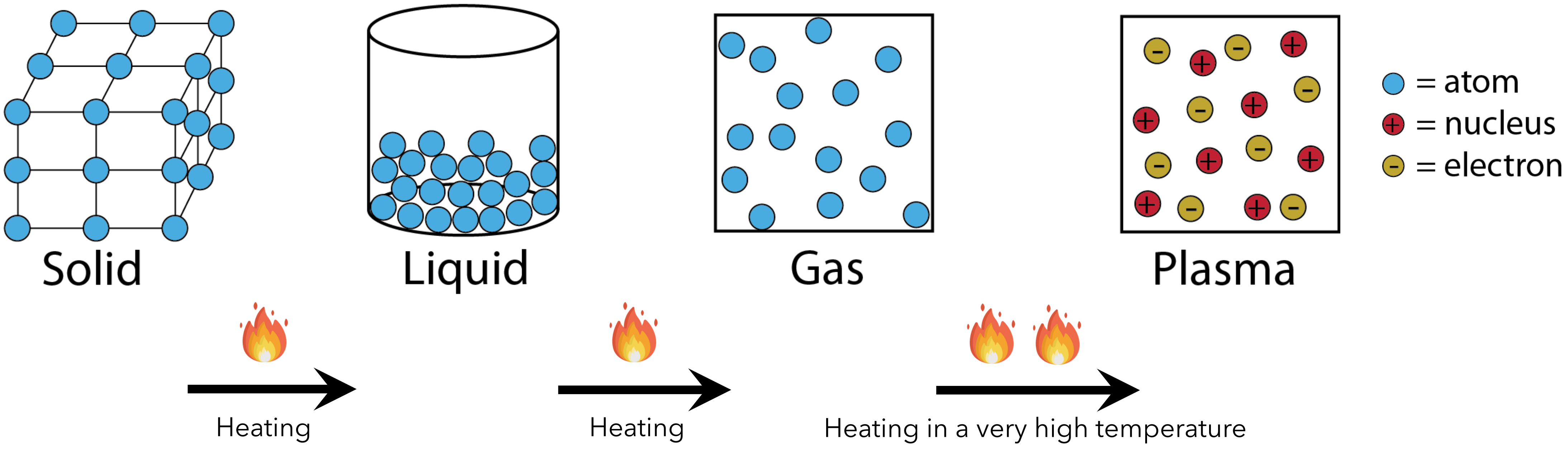
- Understand states of matter
- Classify “Fluid” or “Non-fluid”
- Fluid behavior under shear stress
- Understand the properties of fluid

States of Matter

How many states of matter which naturally occur in the universe?

- The same material can exist in many different forms, depending on factors like the temperature and pressure

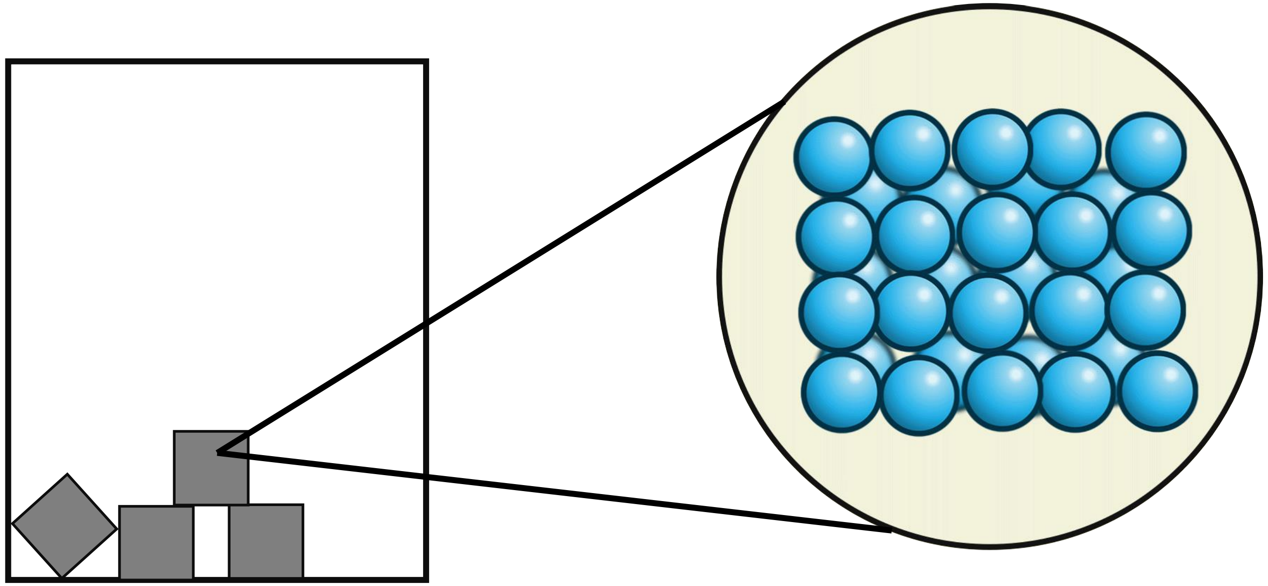
Example: Ice cube



States of Matter

Solids

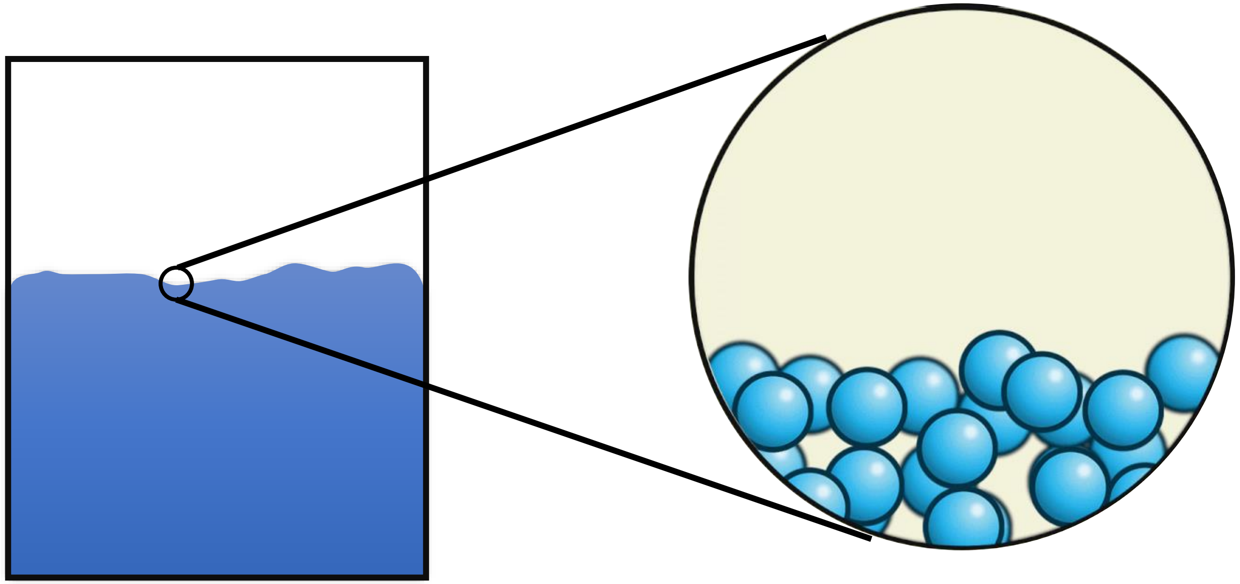
- Not deform into container shape.
- Can be compressed but it's difficult.
- Strong intermolecular bonds preventing molecules from flowing.



States of Matter

Liquids

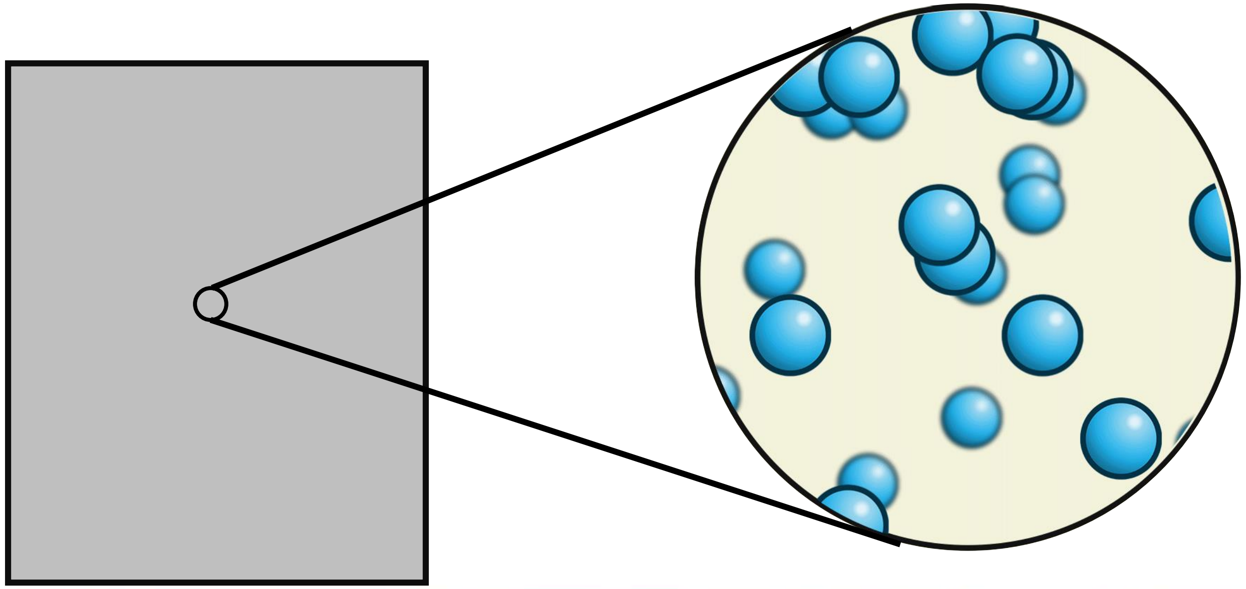
- Deform into a container shape.
- Difficult to compress (consider incompressible)
- Intermolecular bond is weak, allowing molecules to move freely
- Form a free surface



States of Matter

Gases

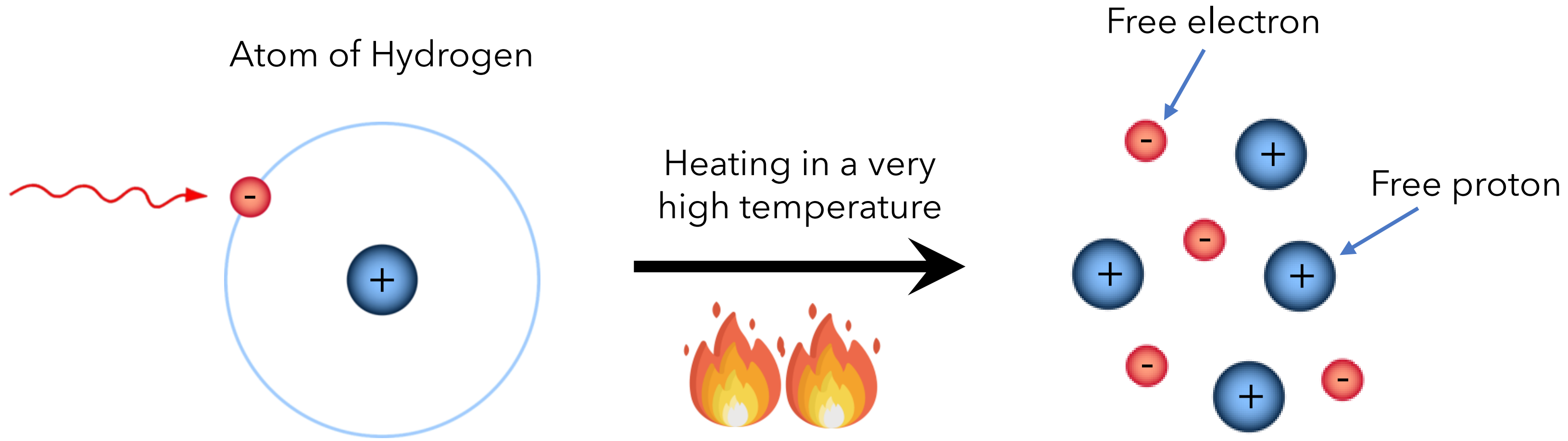
- Spacing of molecular is larger compared to solid and liquid.
- Much easier to compress (consider as compressible).
- Negligible intermolecular bonds allow molecules to move freely throughout container.



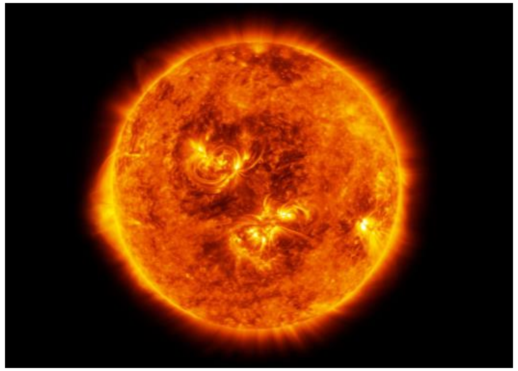
States of Matter

Plasma

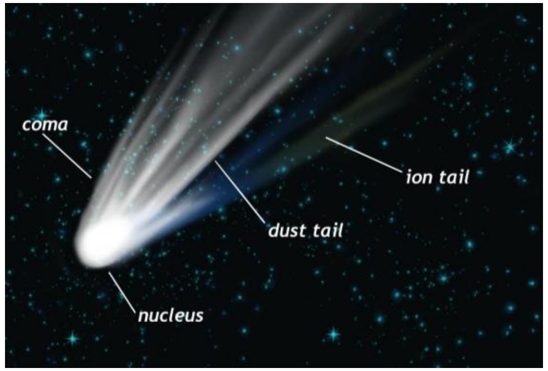
- Charged particle gas
- Gas cannot conduct electricity, but Plasma does.
- Charged particles move in spiral paths along the magnetic field lines.
- Plasma emits radiation in the form of light, heat, and other types of electromagnetic radiation.



States of Matter



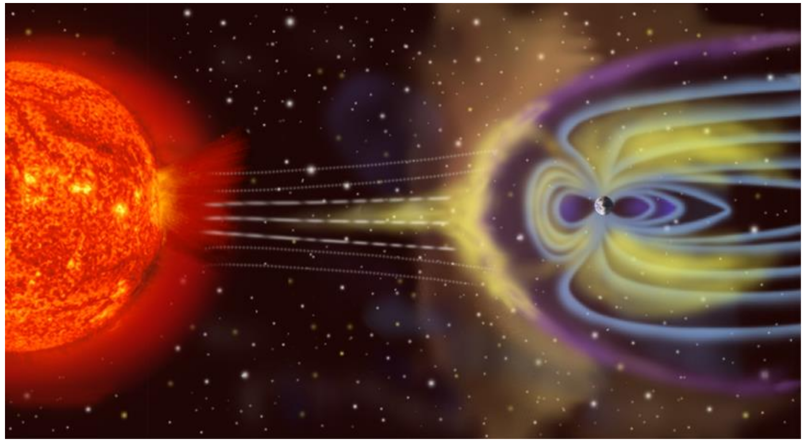
Star



Comet tail

Lightning

Fluorescent Light



Solar wind

Aurora light

Arc Reactor of Ironman
(Science fiction)

Fluid Definition

- What criteria considering fluid?
- Which matters are considered fluid?

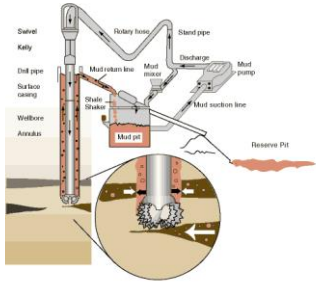
- Fluid is a state of matter characterized by:
  - Fluids flow under the action of a force, and the solids don't – but solids do deform.
  - Fluids lack the ability to resist deformation.
  - Fluids change shape as long as a force acts.
- Matters considered as fluid are Liquid, Gas, and Plasma.

Fluid Definition

- How about the combination of solid and liquid?
- How about the combination of solid and gas?

Ex:

Mixing cornstarch (solid) with water (liquid)



Drilling mud (bentonite) consists of soil (solid) and water (liquid)

Sludge contains a combination of water (liquid) and solid particles (solid)

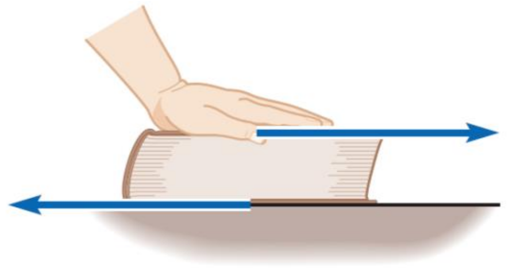
Smoke from factories consists of toxic metal, particle (solid) and gases (gas)

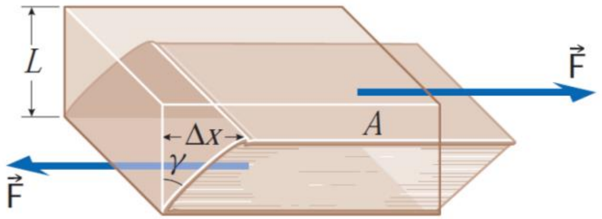
Fluid Definition

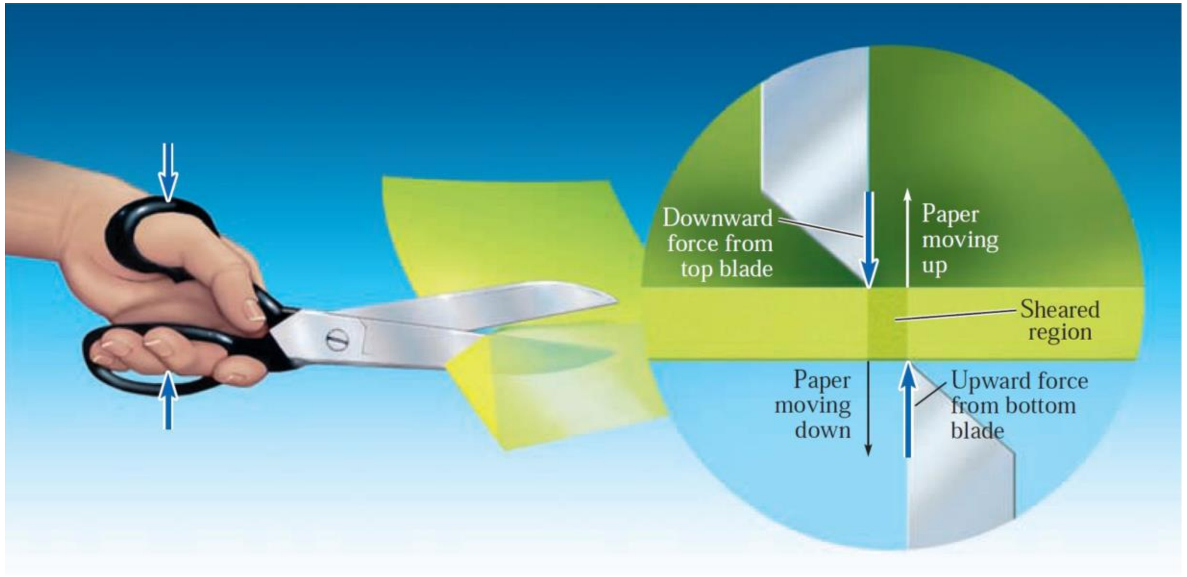
Definition of Fluid in the Context of Fluid Mechanics

❖ Concept of Shearing :

- What is shear?

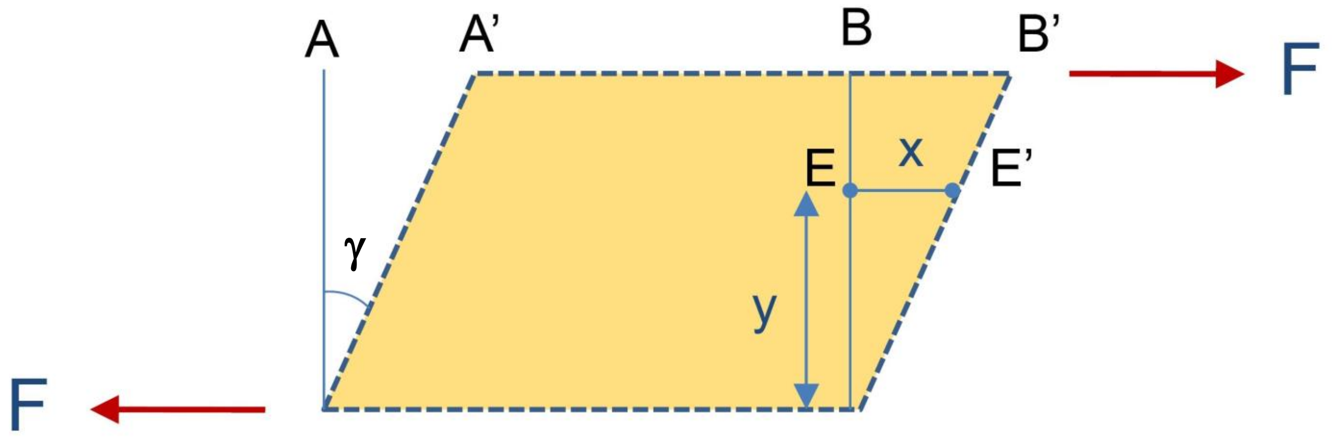






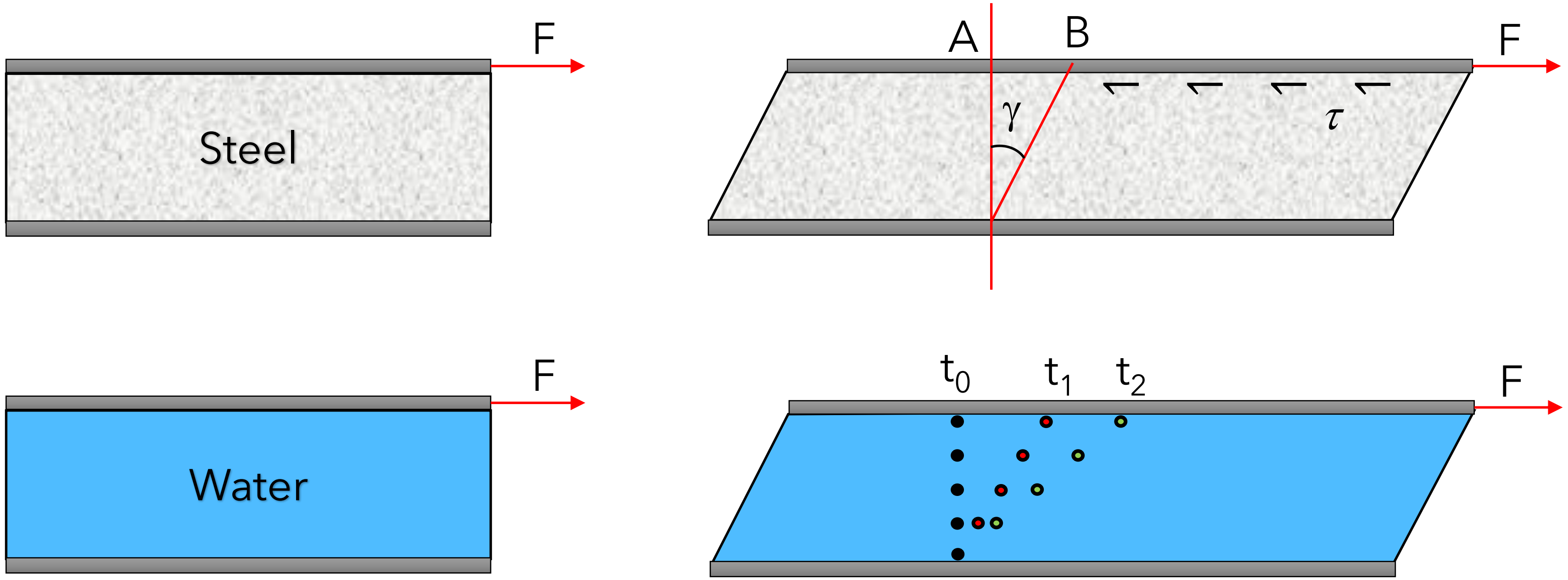
Fluid Definition

❖ Concept of Shearing :



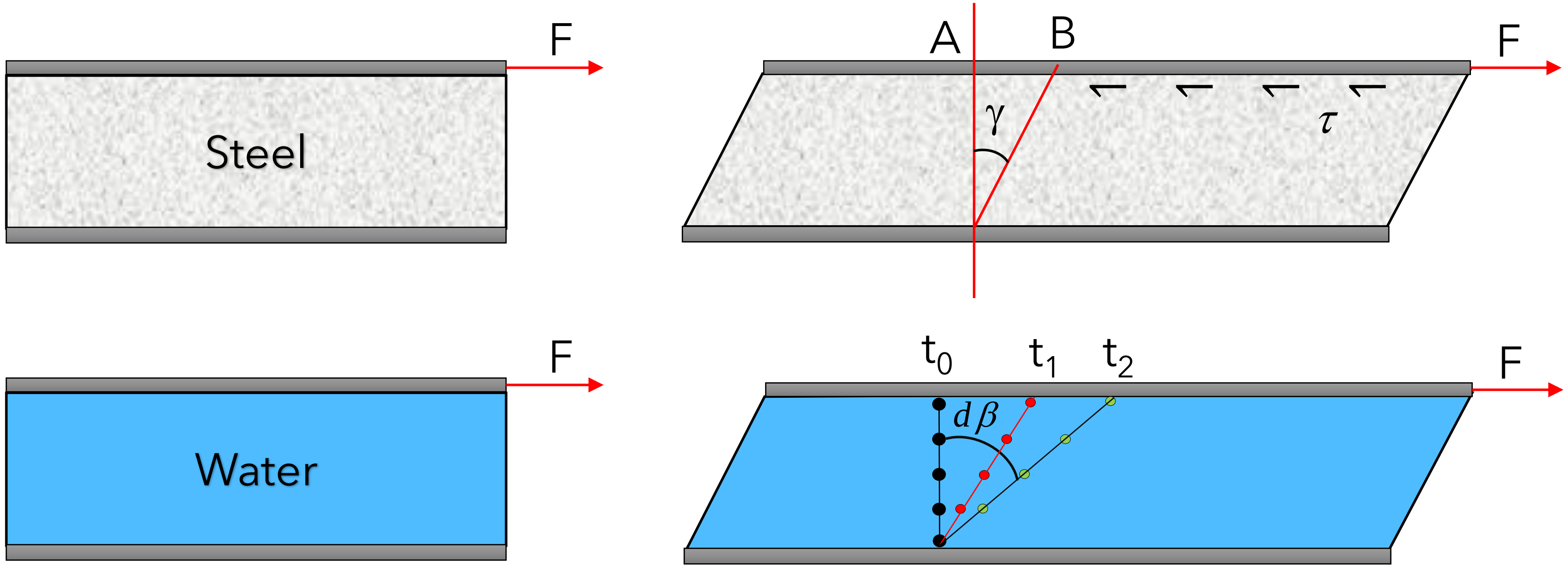
- Shear stress is the force per unit area: $\tau = \dfrac{F}{A}$
- The deformation which shear stress causes is measured in angle (γ) *and* known as shear strain.

Fluid Definition



- For solid, shear strain is constant for a fixed shear stress
- For fluid, shear strain is increased for as long as shear stress is applied – the fluid flows.

Fluid Definition



$$G = \frac{\tau}{\gamma}$$

$\gamma =$ Shear strain

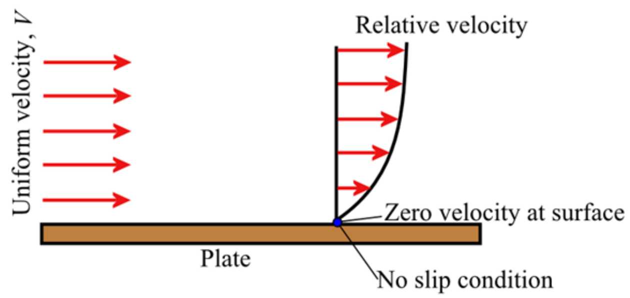
$\dfrac{d\beta}{dt}$ = Strain rate

Hence the definition of fluid can be stated:

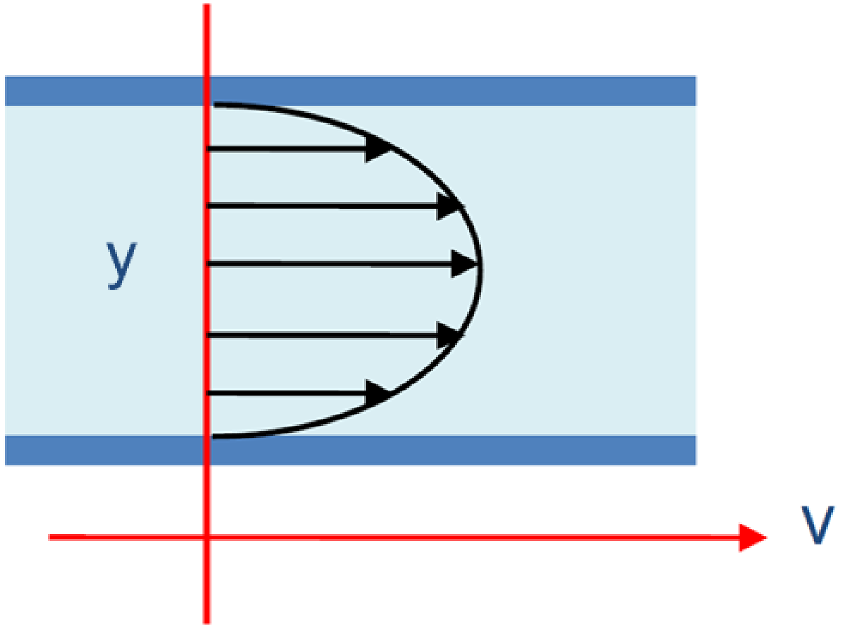
In Fluid Mechanics, Fluid is a substance that deforms continuously (flow) under an applied shear stress.

Fluid in Motion

- Consider a fluid flowing near a wall. e.g., in a pipe
- Fluid next to the wall will have zero velocity for no slip condition.
- Moving away from the wall, velocity increases to a maximum.



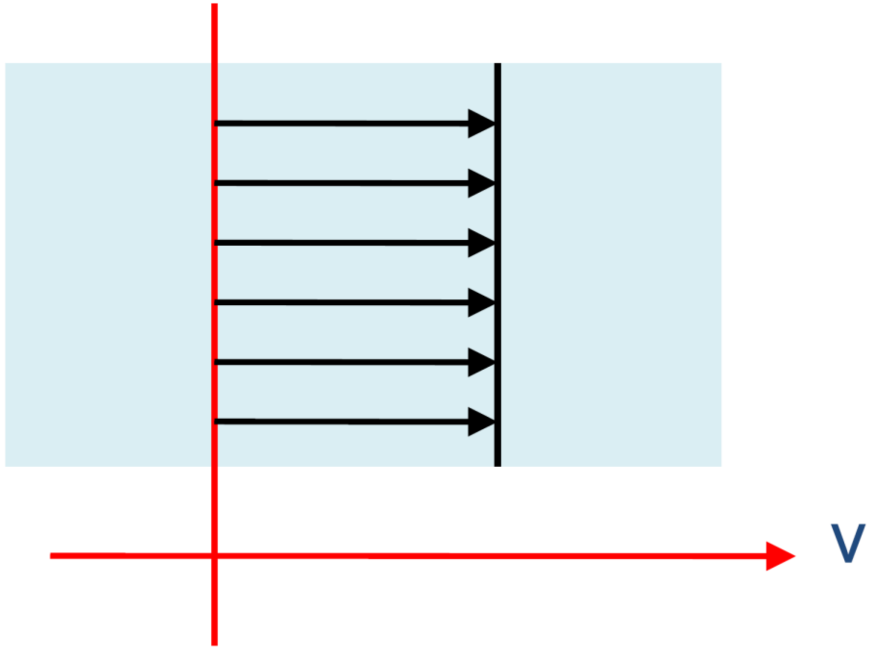
Fluid in Motion



- Plotting the velocity across the section gives "velocity profile"
- Change in velocity with distance is

$$\frac{du}{dy} = \text{Velocity gradient}$$

Fluid in Motion



No velocity gradient, no shear forces.

Fluid Properties

Density

There are three ways if expressing density:

1. **Mass Density**

$$\rho = \frac{m}{V}$$

Where: m = mass of fluid
V = volume of fluid

Units: kg/m^3

Dimensions: ML^{-3}

Typical values:

Water = 1000 kg.m^{-3}
Mercury = 13546 kg.m^{-3}
Air = 1.23 kg.m^{-3}
Paraffin Oil = 800 kg.m^{-3}

Fluid Properties

2. Specific Weight (Unit weight)

$\gamma = \rho g$

Where: ρ = mass per unit volume
g = earth gravitational acceleration

Units: N/m^3 or $kg/m^2/s^2$

Dimensions: $ML^{-2}T^{-2}$

Typical values:

Water = 9999.72 $N.m^{-3}$ at $4^{o}c$
Mercury = 136000 $N.m^{-3}$
Air = 12.07 $N.m^{-3}$
Paraffin Oil = 7851 $N.m^{-3}$

Fluid Properties

3. Specific Gravity

$$G_s = \frac{\rho_{\text{substance}}}{\rho_{H_2O(\text{at } 4^{\text{o}}\text{C})}}$$

Where:

$\rho_{\text{substance}}$ = density of substance

$\rho_{H_2O(\text{at } 4^{\text{o}}\text{C})}$ = density of water at 4 degree Celsius

Units: none

Dimensions: dimensionless , 1

Typical values:

Water = 1
Mercury = 13.6
Paraffin Oil = 0.8

Fluid Properties

Density (ρ)	Unit Weight (γ)	Specific Gravity (G_S)
kg/m^3	kN/m^3	N/A
1000	10	1
800	8	0.8
13600	136	13.6

Note: $g = 10 m/s^2$

Fluid Properties

Viscosity

There are two ways if expressing viscosity:

1. Dynamic Viscosity

Dynamic viscosity is the ability to resist flow when subjected to an applied shear stress.

$$\mu = \frac{\tau}{du/dy}$$

Where: τ = shear stress

$\frac{du}{dy}$ = velocity gradient

Units: N.s/m^2, Pa.s, Centipoise (cP)

Dimensions: $ML^{-1}T^{-1}$

Typical values:

1 cP = 0.001 Ns/m^2

Water = 1.002×10^{-3} Ns/m^2
Air = 1.78×10^{-5} Ns/m^2
Mercury = 1.552 Ns/m^2
Paraffin Oil = 1.9 Ns/m^2

Fluid Properties

2. Kinematic Viscosity

Kinematic Viscosity is a measure of fluid's internal resistance to flow under gravitational forces.

$$v = \frac{\mu}{\rho}$$

Where: ρ = mass per unit volume
μ = dynamic viscosity

Units: m^2/s, Centistokes (cSt)

Dimensions: L^2T^{-1}

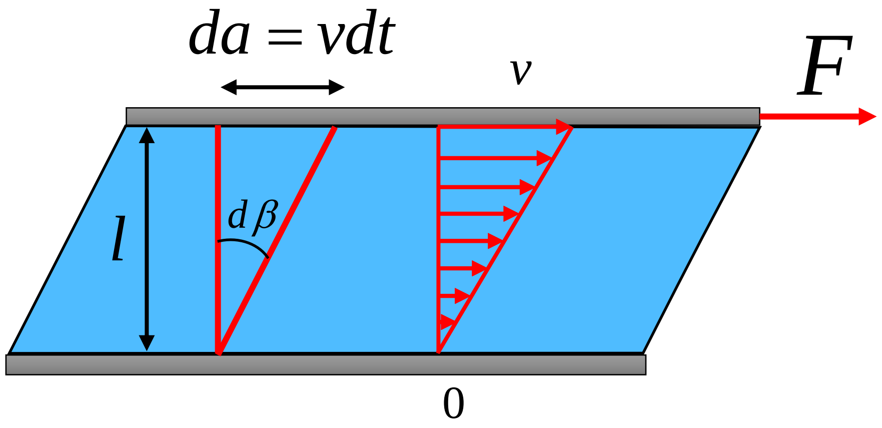
Typical values:

1cSt = 10^{-6} m^2/s

Water = 1.002×10^{-6} m^2/s
Air = 1.46×10^{-5} m^2/s
Mercury = 1.145×10^{-4} m^2/s
Paraffin Oil = 2.375×10^{-3} m^2/s

Fluid Properties

Viscosity

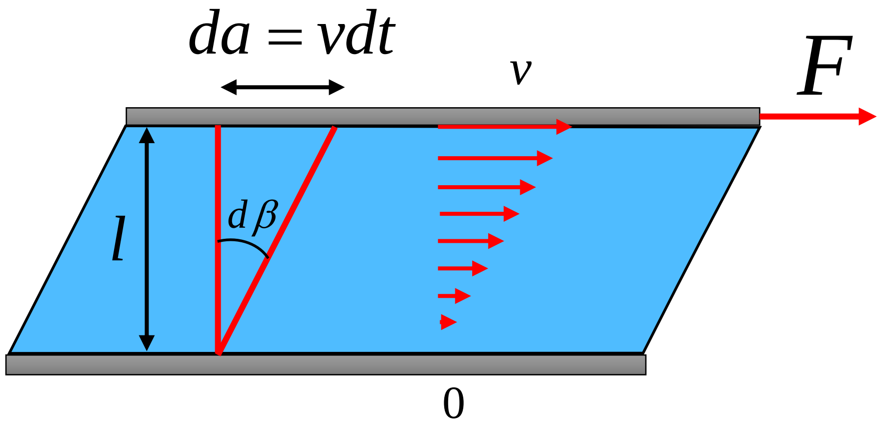


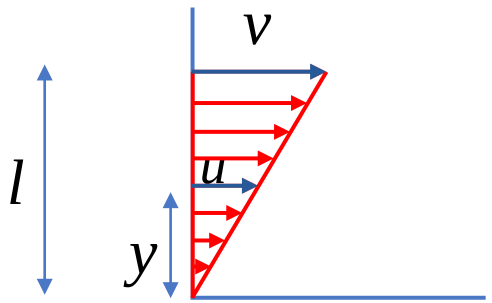
$$\frac{v}{u} = \frac{l}{y} \Leftrightarrow u = \frac{y.v}{l} \Leftrightarrow \frac{du}{dy} = \frac{v}{l}$$

$$d\beta \approx \tan\beta = \frac{da}{l} = \frac{vdt}{l} = \frac{du}{dy}dt$$

$$d\beta = \frac{du}{dy}dt \quad \Leftrightarrow \quad \frac{d\beta}{dt} = \frac{du}{dy}$$

Fluid Properties





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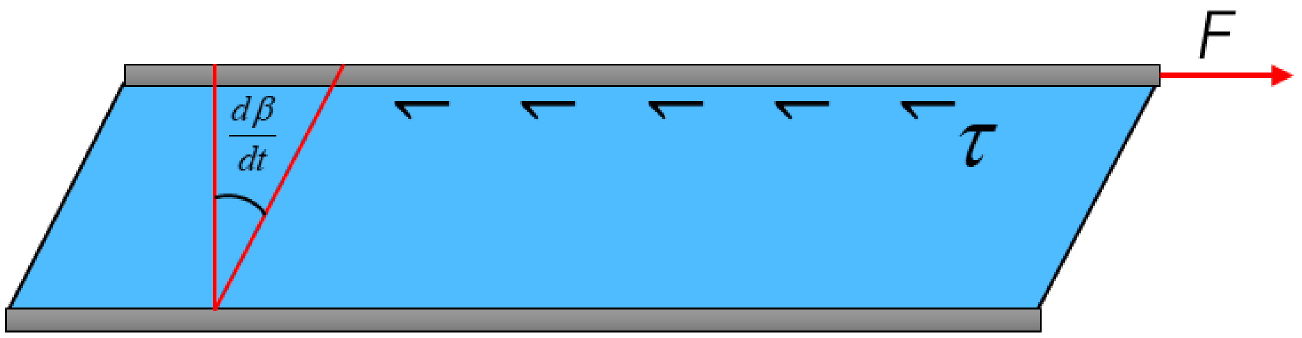
Fluid Properties



$$\frac{d\beta}{dt} = \frac{du}{dy}$$

$\frac{d\beta}{dt}$ = Strain rate

$\frac{du}{dy}$ = Velocity gradient

μ = Viscosity

$$\tau = \frac{F}{A}$$

$$\mu = \frac{\tau}{\frac{d\beta}{dt}} \Leftrightarrow \mu = \frac{\tau}{\frac{du}{dy}} \Leftrightarrow \tau = \mu \times \frac{du}{dy}$$

Fluid Properties

- **Newtonian Fluid** is a fluid which obeys Newton's Law of viscosity. (Sometimes also called **Real fluid**)
- Newtonian fluid have a constant value of viscosity (μ)
- Newton's law of viscosity:

$$\tau = \mu \times \frac{du}{dy}$$

Fluid Properties

- **Non-Newtonian Fluid** is a fluid do not have a constant (μ).
- They do not obey Newton's Law of viscosity.
- They do obey a similar relationship and can be placed into several clear categories.
- The general relationship is:

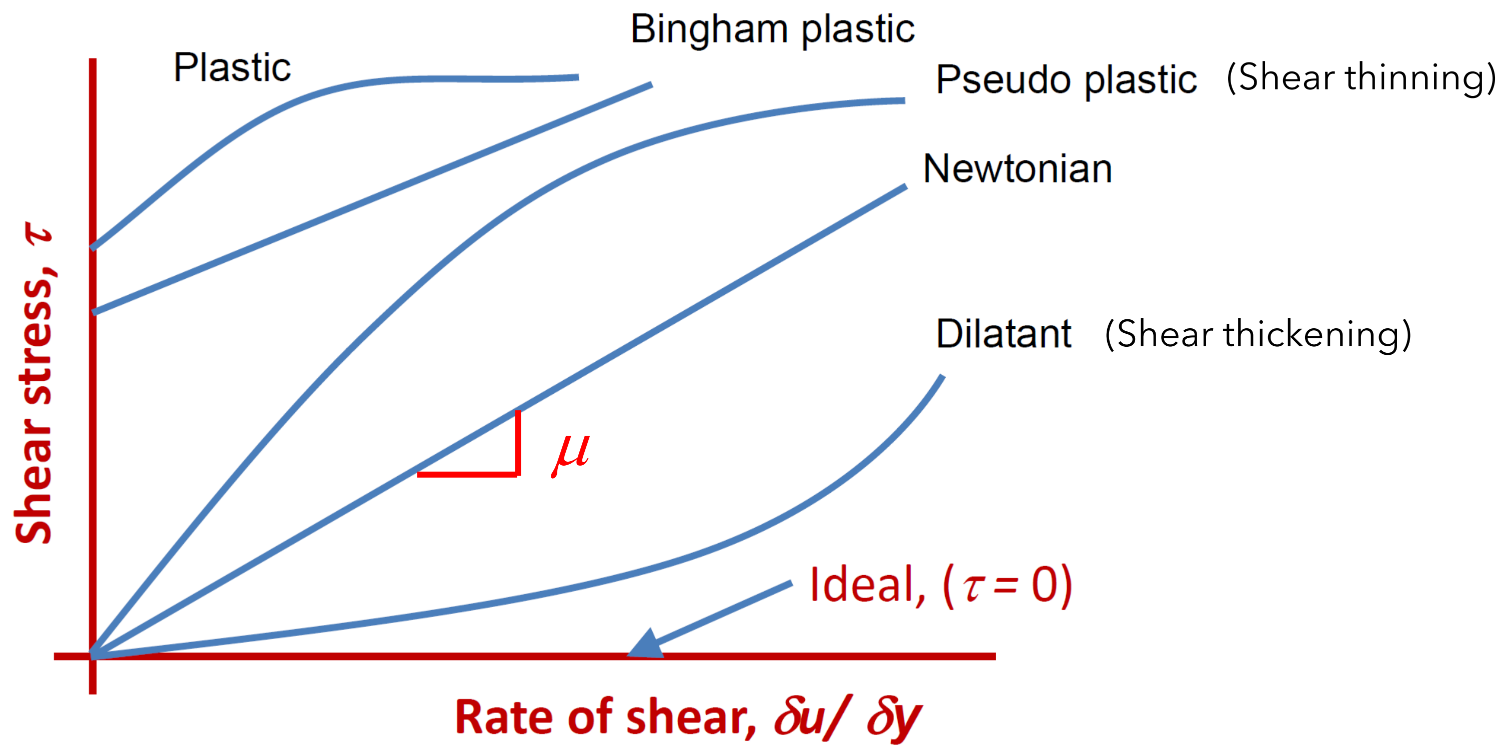
$$\tau = A + B\left(\frac{du}{dy}\right)^n$$

Where *A*, *B* and *n* are constants.

- For Newtonian fluids: A=0, B=μ and n=1

Fluid Properties

This graph shows how μ changes for different fluids.



$$\mu = \frac{\tau}{\frac{du}{dy}}$$

Fluid Properties

❖ Shear thinning property = viscosity decreases under shear stress.

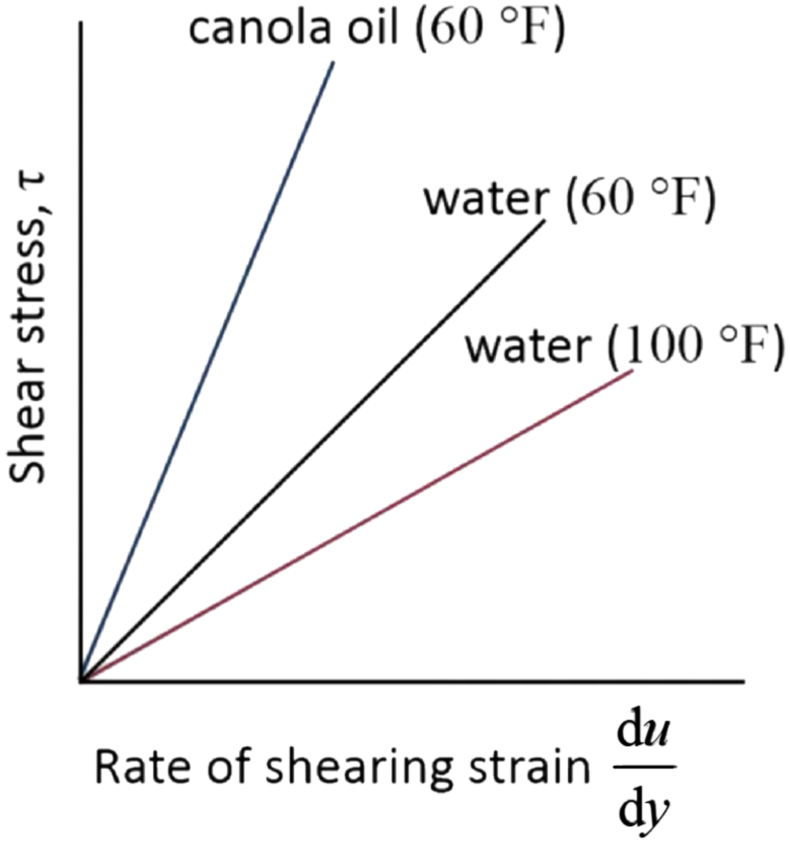
- Ex: molten polymer, polymer solutions, ketchup, drilling fluid, and quicksand.

❖ Shear thickening property = increase of apparent viscosity at high shear stress.

- Ex: mixture of cornstarch and water.

Fluid Properties

- In general, viscosity depends on a fluid's state, such as its temperature, pressure, and rate of deformation.



Fluid Properties

Viscosity of Liquids

- Increasing the temperature of a fluid $\Rightarrow$ decreases viscosity because increased temperature allows molecules to more easily escape the attractive force of adjacent molecules.

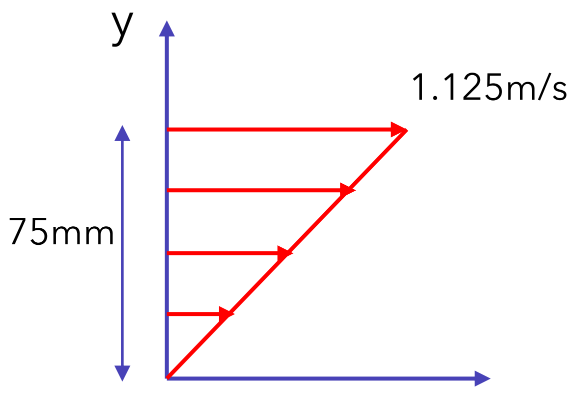
Viscosity of Gases

- If temperature increases the momentum exchange between layers will increase thus increasing viscosity.
- Increase temperature, gas molecules have more random motion, which results in more inter-molecular collisions.

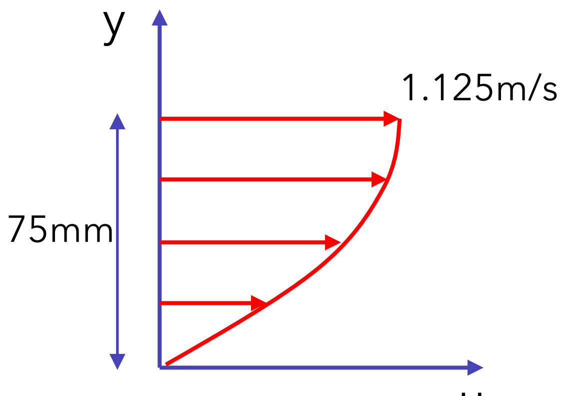
- **Ex1:** If $6x10^6$cc of oil presents 47kN.

  Determine:
  - unit weight, γ
  - mass density, ρ
  - relative density (specific gravity, Gs)

- **Ex2:** A fluid has an absolute viscosity of 0.048 Pa.s. Calculate the velocity gradient and the shear stress at the wall and at the points situated at 25mm, 50mm, 75mm.
  - a.) the distribution of linear velocity.
  - b.) the distribution of parabolic velocity.
    The velocity at 75mm is 1.125m/s.



(a)



(b)

Hints:
- $y = au + b$
- $u = ay^2 + by + c$

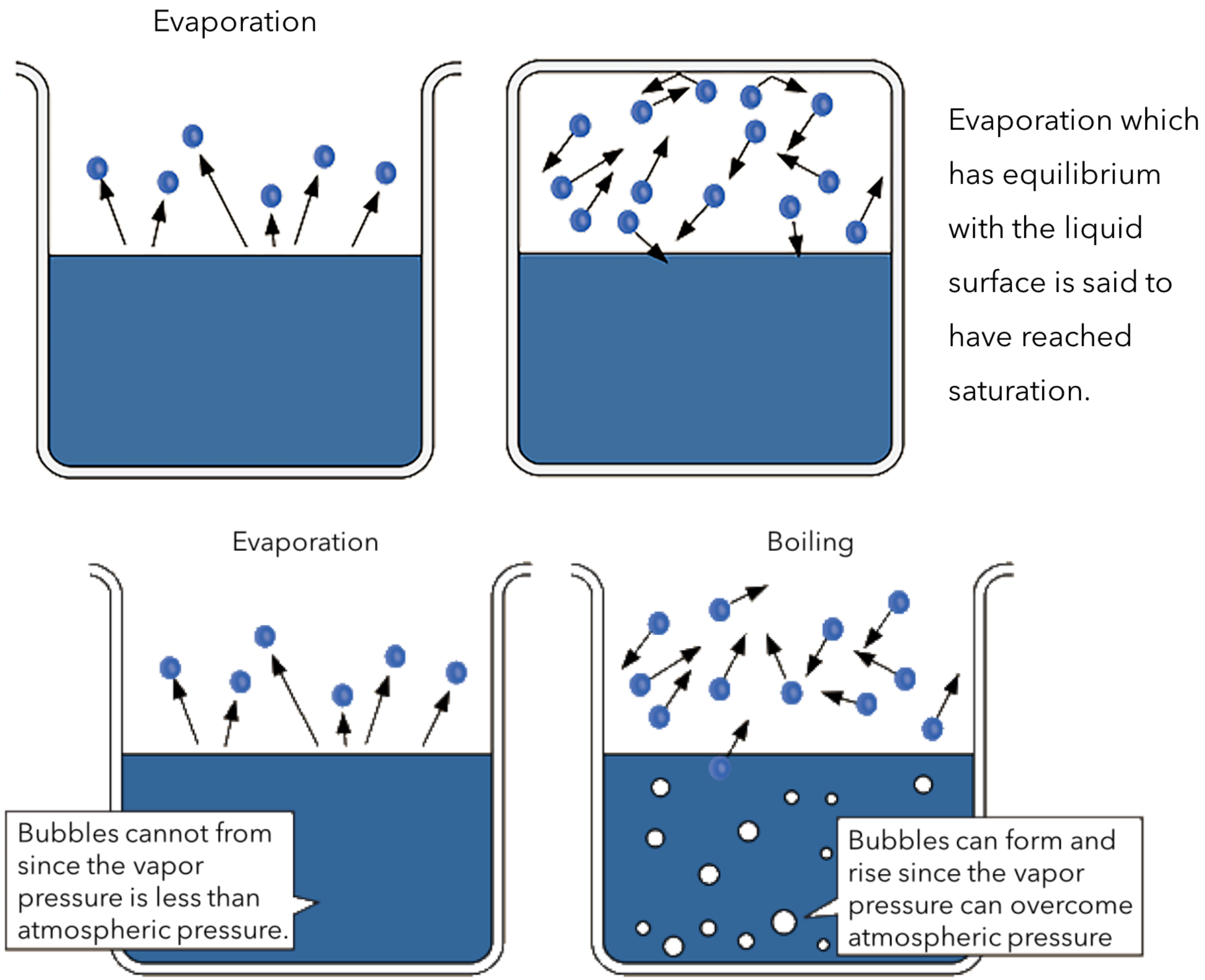
Fluid Properties

Vapor Pressure & Cavitation

- We have a liquid in an open container, the it will eventually evaporate.
- The water molecules at the surface of the liquid have enough kinetic energy to break free from the surface.
- Since this process depends upon the kinetic energy of the molecules, the evaporation rate increases → more molecular kinetic energy.

(if we heat the water, water evaporates quickly because hot water has more kinetic energy)

Fluid Properties



- The process of evaporation in a closed container will proceed until there are as many molecules returning to the liquid as there are escaping.
- When the vapor pressure is low and the pressure inside the liquid is equal to atmospheric pressure plus the liquid pressure, bubbles of water vapor cannot form. But at the boiling point, the saturated vapor pressure is equal to atmospheric pressure, bubbles form.

Fluid Properties

- Liquid with a higher vapor pressure will evaporate at a higher rate.
- Vapor pressure is the direct measure of the volatility.

Vapor Pressure at 20 °C

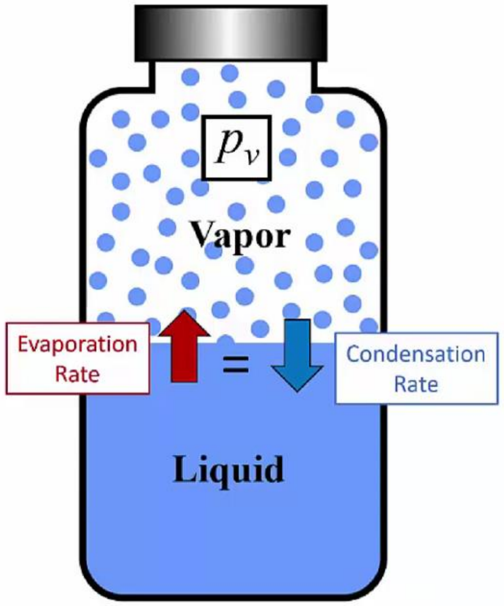
Methanol	P_v = 13.02kPa
Ethanol	P_v = 5.95kPa
Water	P_v = 2.4kPa

Fluid Properties

- **Vapor pressure** is the pressure exerted by the vapor phase of a substance when it is in equilibrium with its liquid, with the rates of evaporation and condensation balanced, at a specific temperature.

e.g. At atmospheric pressure, P = 101.3 kPa
Water boils at 100 °C.

e.g. Pressure at Top of mount Everest about 31kPa
The water boils at 70 °C on the mount Everest.



Relationship between vapor pressure and temperature of water

T (°C)	P_v (kPa)
0	0.611
10	1.227
20	2.337
30	4.242
40	7.375
50	12.34
60	19.92
70	31.16
80	47.35
90	70.11
100	101.3

Fluid Properties

Cavitation

- Cavitation is a physical phenomenon that involves the formation and collapse of vapor or gas-filled cavities (bubbles) in a liquid.
- This process occurs when the pressure of the liquid falls below its vapor pressure, leading to the formation of bubbles. When these bubbles move to regions of higher pressure, they collapse or implode, generating shock waves and high-speed liquid jets.

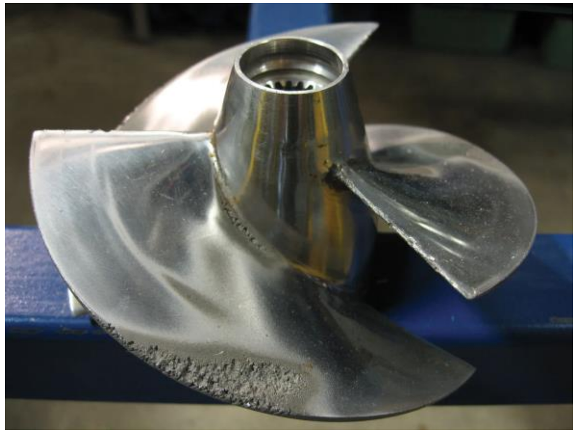
Fluid Properties

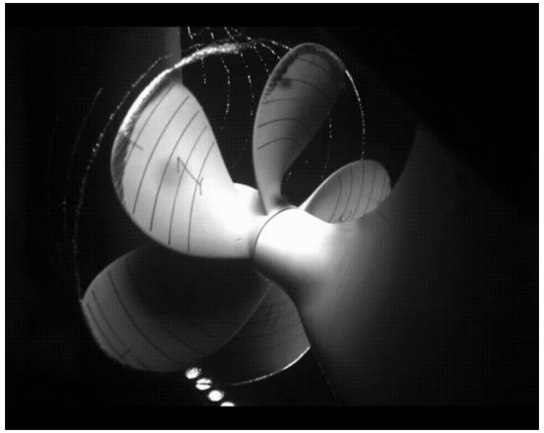
Cavitation

Fluid Properties

Cavitation

Pumping Impeller





Propeller

Fluid Properties

04/03/2024

Surface Tension

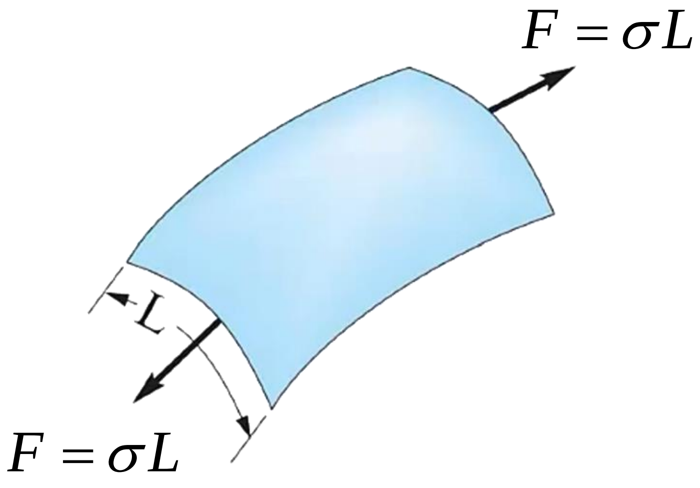
- Surface tension is the force that causes small liquid drops and bubbles to tend to form into spheres.
- Liquid molecules have cohesive forces. At an interface with a gas there appears to be an elastic membrane at the surface.



Fluid Properties

Surface Tension

- Surface tension is denoted as σ - units: N/m
- Modelled as a membrane, where surface tension is the force per unit length of the membrane.
- Water-air interface, σ = 0.073N/m (at 20°C) that enough tension to support an insect and small metal object at a surface.

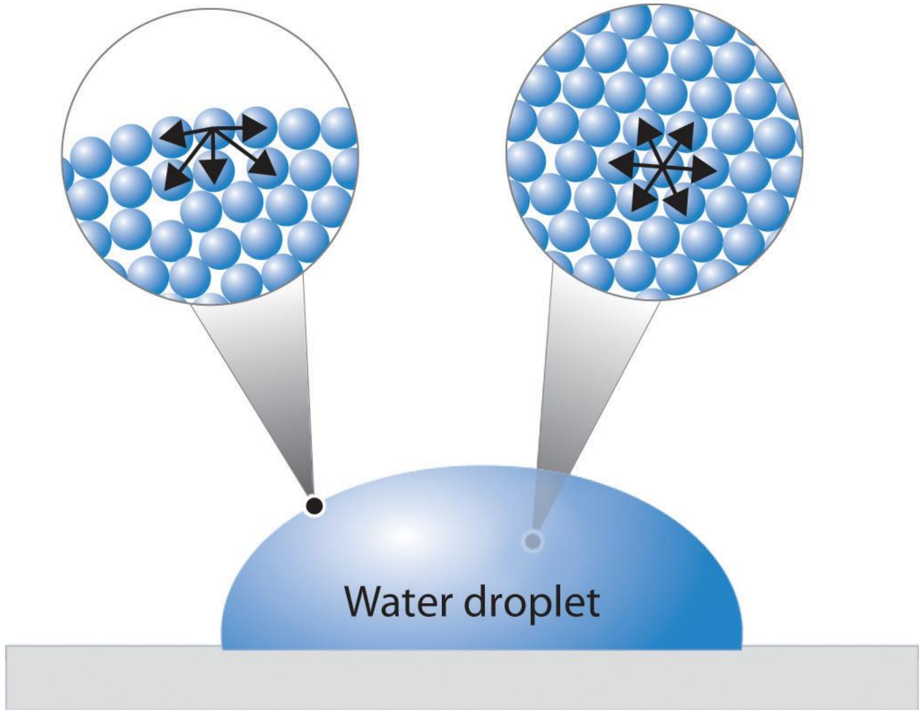


Water strider

Fluid Properties

Surface Tension

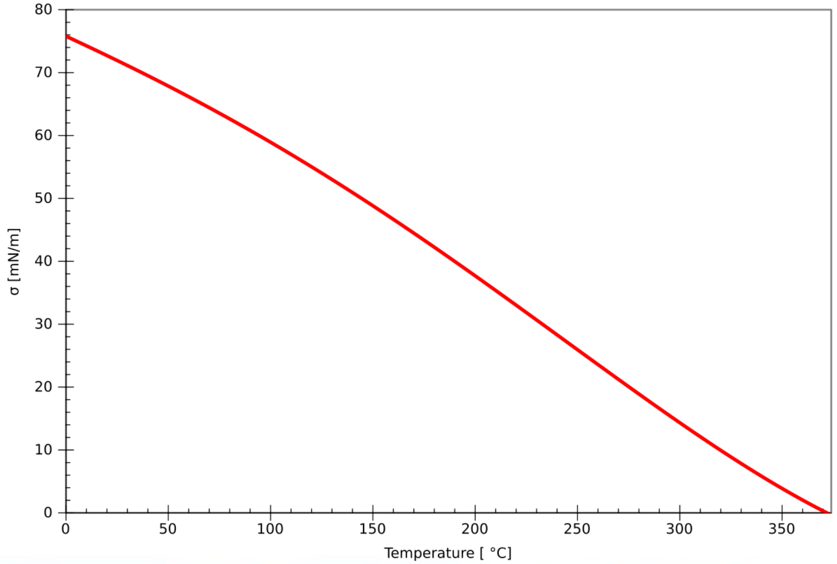
- Surface tension is caused by the cohesive force between liquid molecules.
- Molecules away from the interface are pulled uniformly in all direction.
- Molecules at the interface are pulled sideways and inward.
- At the interface, the outward force is week because the molecules in the gas are more dispersed.



Fluid Properties

Surface Tension

- Surface tension is a function of temperature
- Decrease with temperature
- More likely to be able to place paperclip on the surface of cold water rather than hot water.



Surface Tension - Water in contact with Air

T (^oC)	σ (10^{-2} N/m)
0	7.56
5	7.49
10	7.42
20	7.28
30	7.12
40	6.96
50	6.79
60	6.62
70	6.44
80	6.26
90	6.08
100	5.89

Fluid Properties

Surface Tension

- Surface tension can be strongly affected by contaminants
- Detergents reduce the surface tension

Experiment of water droplet on wax paper

Wooden stick without detergent

Wooden stick with detergent

Fluid Properties

Surface Tension

- Surface tension causes the pressure inside a droplet to increase.

- Example:

A droplet of water with radius R = 0.5mm at 20°C. Determine the pressure inside the water droplet. Ignore the effect of gravity. Atmospheric pressure is 101.3 kPa.

Fluid Properties

Surface Tension

- Solution

$$\sum F = 0 \qquad \Delta p A_c = \sigma L$$

$$\Delta p \pi R^2 = \sigma(2\pi R)$$

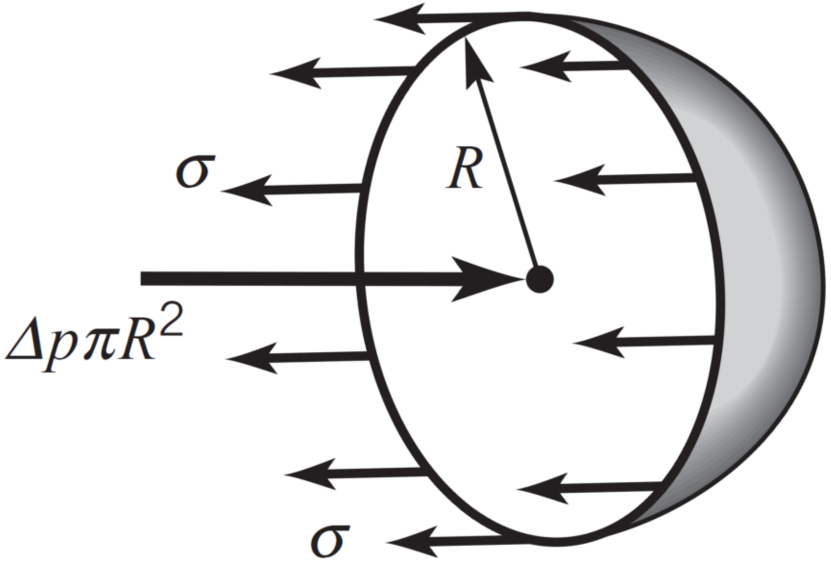
$$\Delta p = \frac{2\sigma}{R}$$

$$\Delta p = \frac{2 \times 0.0728 N/m}{0.0005 m}$$

$$\Delta p = 291 N/m^2 = 0.291 kPa$$

$$p_{droplet} = \Delta p + p_{atm} = 0.291 + 101.3$$

$$p_{droplet} = 101.591 kPa$$



Free body diagram of half water droplet

Pressure inside droplet is 291 Pa above atmospheric pressure

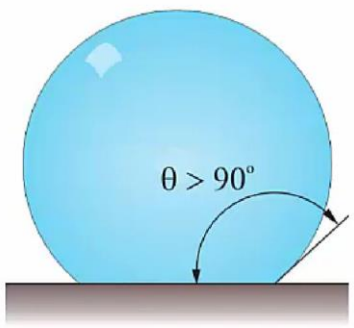
Fluid Properties

Contact Angle and Wettability

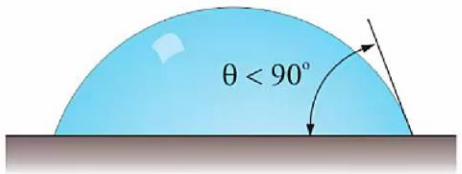
- When a liquid was put on a surface, its behavior is quite different depending upon the wettability of the surface.

θ >90° is the characteristics of Non-wetted surface and also called Hydrophobia material

θ <90° is the characteristics of Wetted surface and also called Hydrophilic material.



Non-wetted surface



Wetted surface

The End of Section